Introduction to Earth System Science

What is Earth System Science

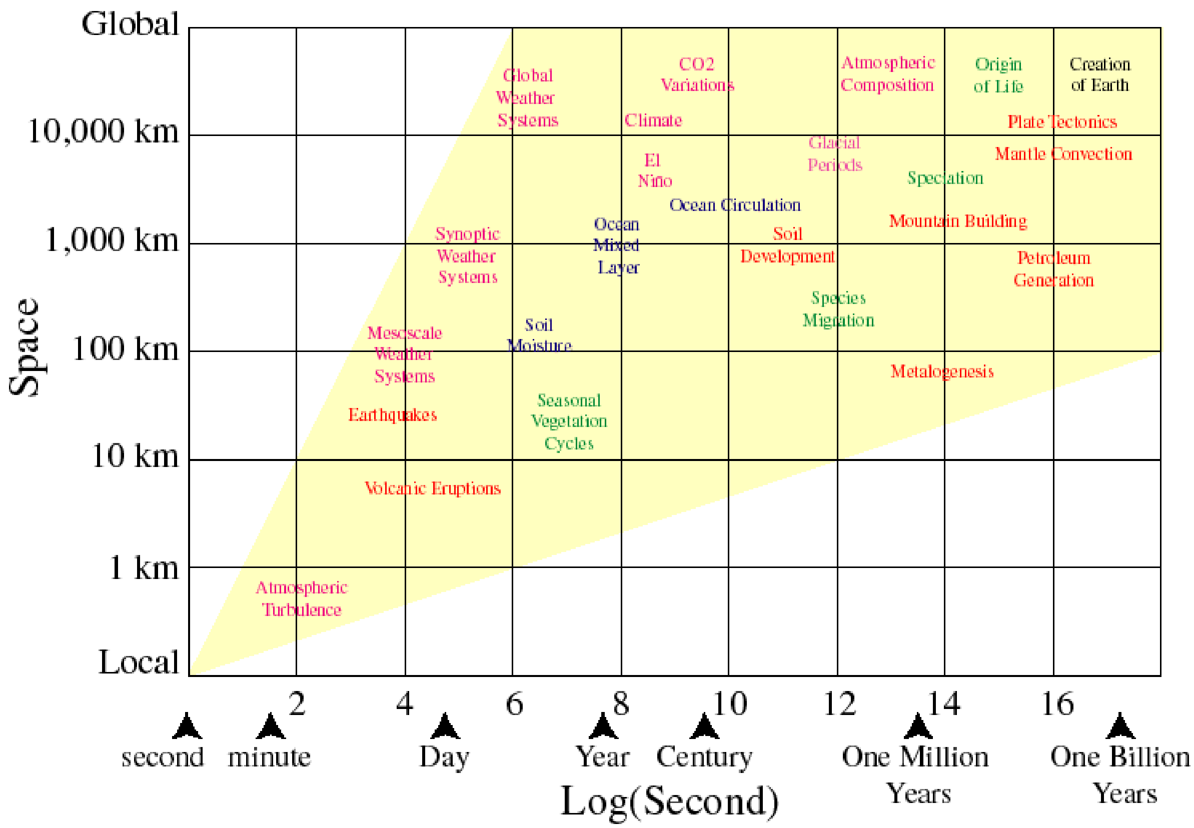
Defining Earth System Science or alternately the Science of Earth Systems (ESS) is not simple. ESS is a new scientific discipline, emerging in the 1980's and as such is still somewhat of an abstract entity. It represents a new scientific view - the Earth as an integrated system whose study must transcend traditional discipline boundaries. The ultimate goal of ESS is to develop a deeper understanding of the processes responsible for the evolution of the Earth on all timescales (NASA Advisory Council, 1988).

Earth System Science embodies two fundamental conclusions of contemporary Earth Science research (NASA Advisory Council, 1988):

1. Change on the planetary scale is the result of interactions and feedbacks among the Earth's different systems - the atmosphere, ocean, crust, mantle, cryosphere, and biological systems. (Extraterrestrial changes such as variations in solar illumination and asteroid impacts also are major causes of planetary change.)
2. Changes on any temporal (time) scale involve interaction among Earth system processes that occur on diverse timescales.

An example of the characteristic time and spatial scales which important earth processes operate is shown below.

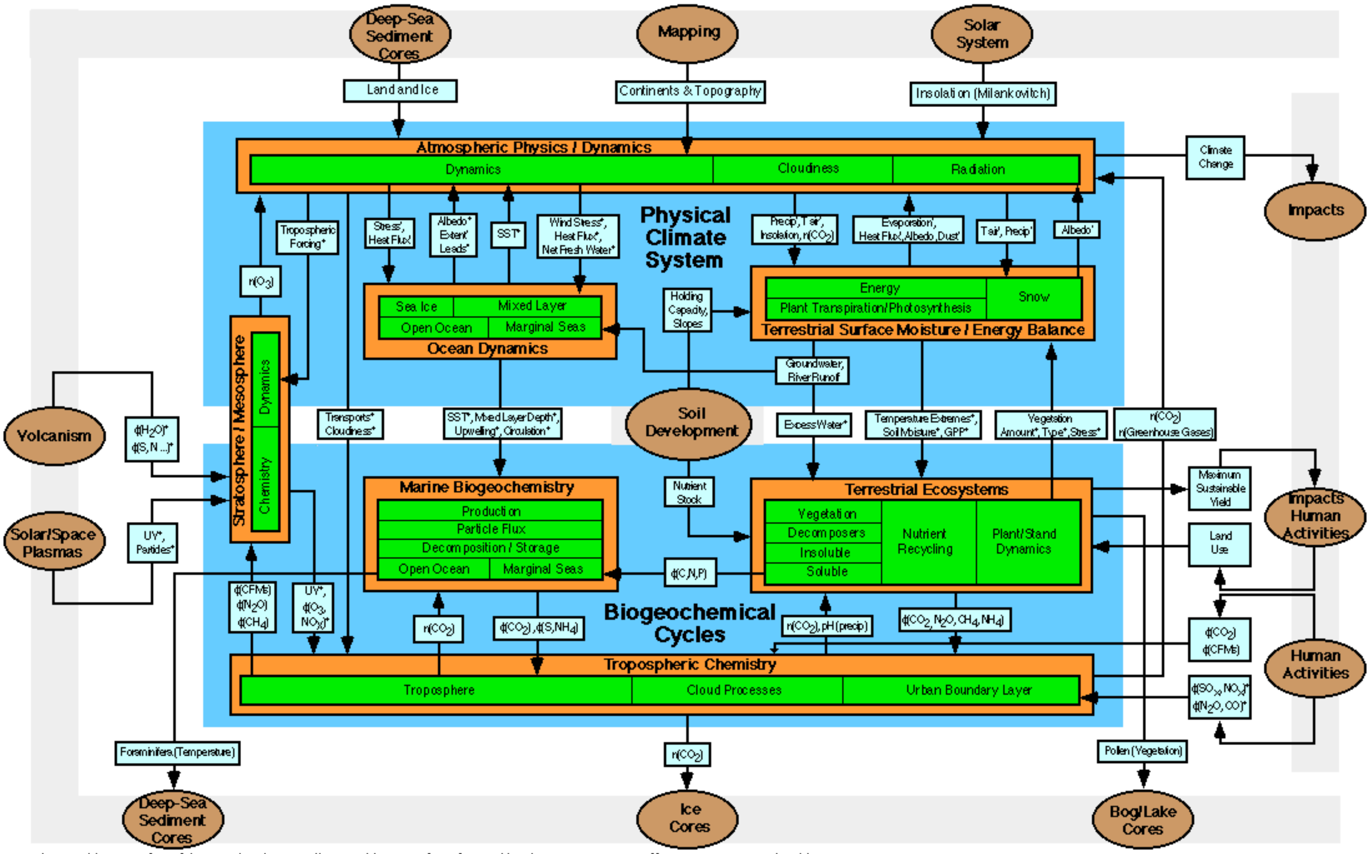
Earth System Processes: Characteristic Space and Time Scales



In order to study and understand planetary changes, it is necessary to integrate traditional academic disciplines and take a broader, global view. This is the task of ESS. It aims to *understand* the *causes*, *processes*, and perhaps *the limits of variability* of planetary change. In turn this understanding may help *enable improved predictions* of future planetary-scale change.

Below is what has become known as the Brethren Diagram. It depicts the interconnected (and complex) nature of earth system processes. In this class we will take a detailed look at some of the processes and interactions.

CONCEPTUAL MODEL of Earth System process operating on timescales of decades to centuries



' = on timescale of hours to days * = on timescale of months to seasons ϕ = flux n = concentration

Lest we kid ourselves, the societal, and thus political, motivation for Earth System Science is to develop a comprehensive and integrated program to address a scientific research area of great urgency - global change on **time-scales of decades to centuries**. The following statement issued by the Intergovernmental Panel on Climate Change (IPCC) in 1995 underscores the importance of understanding global change on these time scales.

> "Our ability to quantify the human influence on global climate is currently limited because the expected signal is still emerging from the noise of natural variability and because there are uncertainties in key factors. These include the magnitude and pattern of long term natural variability and the time-evolving pattern of forcing by, and response to changes in the concentrations of greenhouse gases and aerosols, and land surface changes. ***Nevertheless, the balance of evidence suggests that there is a discernible human influence on global climate***. (IPCC, 1995)

Despite intense interest in global change on decade to century time scales it is important to comprehend the history of Earth System changes recorded in the geologic record. The geologic record allows potential human impacts to be placed in their geologic context. Thus an important component of Earth System Science, but one often neglected by non-geologists, is the history of the earth. The brevity of human existence on Earth, and even more so the 100 years of the instrumental record of climate variability, compared to the age of the earth is striking.

In his book *Time's Arrow* Stephen Jay Gould rightly credited the writer John McPhee in *Basin and Range* with the most striking metaphor for the concept of geologic (aka deep) time. Consider the earth's history as the old measure of the English yard, the distance from the king's nose to the tip of his outstretched hand. One stroke of a nail file on his middle finger erases human history.

A Broader Perspective

Because Earth System Science has recently emerged as a scientific discipline, we do not have the benefit of a century or so of separation from which to look back and assess the formation of Earth System Science in its broader historical context. Let me just say in a few words of some larger historical trends that may have helped lead to the concept of Earth as a system of interconnected systems.

Certainly, only 100 years ago the idea that mankind could have an appreciable impact on the planetary or global environment would have been considered far-fetched. The United States a century ago was still in a process of vigorous expansion. In 1845 the editor of the Democratic Review, John O'Sullivan printed a phrase that would color the way the American people would see themselves for the next 150 years and lead to the Spanish-American war. He wrote, "fulfillment of our manifest destiny to overspread the continent allotted to us by Providence for the free development of our yearly multiplying millions". The point here is not to pass judgment on the correctness of this doctrine, but rather to point out that it embodied the idea that humankind could tame a vast, nearly limitless, nature, through 'progress'. The concept of a finite earth, and one in which humankind could actually have a negative impact on a global environment is hard simply does not fit into the world-view which is captured exquisitely in the painting *American Progress* by John Gast (1872).

In John Gast's "American Progress," (1872) a diaphanously and precarious clad America floats westward through the air with the "star of empire" on her forehead. She has left the cities of the east behind, and the wide Mississippi, and still her course is westward. In her right hand she carries a school book-- testimonial of the national enlightenment, while with her left she trails the slender wires of the telegraph that will bind the nation. Fleeing her approach are Indians, buffalo, wild horses, bears, and other game, disappearing into the storm and waves of the pacific coast. They flee the wondrous vision--the star "is too much for them."--Precis of a contemporary description of this painting by George Crofutt who Distributed his engraving of it widely.

So what caused, in less than a century, such a dramatic change in the way humankind viewed its relationship to the earth? In his 1994 book *Pale Blue Dot,* Carl Sagan points to a single picture - the picture of Earth shot by Apollo 17 Astronauts as humans returned from the Moon for the last time - as a defining moment in human history. For it is this picture that revealed to us that our world was a solitary planet surrounded by the hostile infinity of space. Whether or not, a single photograph can be credited with forever changing our relationship with Earth is debatable. However, certainly in this period popular culture did embrace this concept of the earth as is embodied in R. Buckminster Fuller's *An Operating Manual for Spaceship Earth*.

Probably the most requested picture of the Earth, this picture was taken by the Apollo 17 astronauts as they left earth orbit en route to the Moon. It was taken on Dec. 7, 1972. (NASA photo number(s): 72-HC-928, 72-H-1578, or AS17-148-22727)

Poetic waxing aside, Earth System Science arose because of several developments (NASA Advisory Council, 1988).

- Maturity of the traditional academic disciplines (geography, geology, biology, oceanography, meteorology, etc.) comprising ESS. As these disciplines matured their interdependence became more obvious to those working within their bounds. In fact, the interdisciplinary nature of the Earth System Science disciplines has been known since at least the last century. The idea that human activity might be change the climate was recognized at least 100 years ago (Weart, 1997). In some sense, the development of Earth System Science is a modern revival of scientists who are broad generalists, not narrow specialists. Charles Darwin, for instance, made significant contributions not only to biology, but also to geology. However, it has only been recently that scientists have had to confront major contributions from fields outside their own to make significant inroads into their own research - hence the need for integrating science across traditional academic boundaries.

- The availability of new earth observations from space that are both global and synoptic.

- The availability of computer power necessary to allow the development of the complex quantitative models necessary to simulate earth system processes.

- The availability of new communications (e.g. the Internet) that allow for the development of extensive Earth Science Information Systems and easy collaboration between scientists working in different locations and disciplines

- THE REALIZATION THAT HUMAN ACTIVITY HAS GLOBAL IMPACTS

Earth System Science Education

So far we have described how the Science of Earth Systems has arose, but how does this translate into education about the Earth System. One important facet of Earth System Science is that it does recognize a societal dimension and as such proper education is key. There is recognition that there is a need for a orderly, comprehensive, interdisciplinary Earth System Science and Global Change curriculum. This curriculum is necessary not only to educate future scientists, but also to provide the education necessary to understand complex ESS issues to individuals who will be responsible for policy decisions in industry and government.

With this philosophy in mind, this class has the goal of providing a basic introduction to Earth System science. The intent of the course is to provide an understanding of Earth System Science that can be used to help you be able to evaluate current and future global environmental change issues. This class strives to go beyond presenting simply a body of static knowledge. I hope to be able to help you:

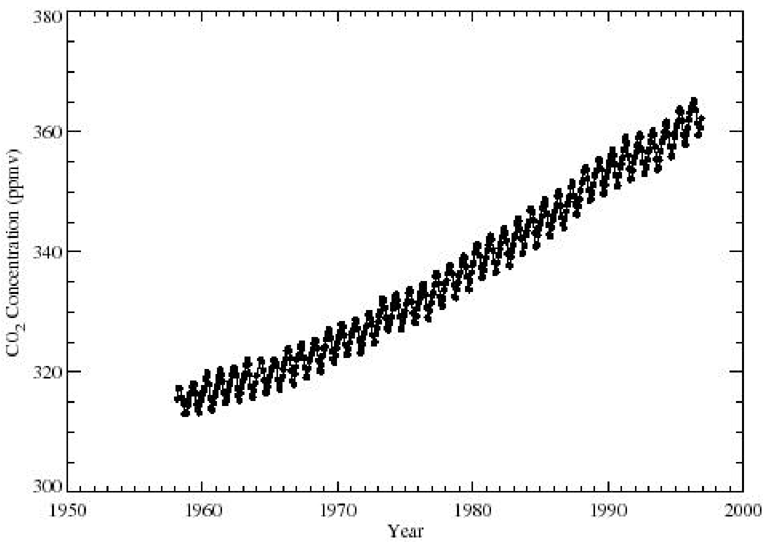
- know WHERE and HOW to look for information on ESS subjects

- learn how to approach examining an ESS process or problem to find a solution or answer (e.g. learn to think like a physical scientist which is something I really didn't learn how to do well until I got to graduate school.)

Specifically, the course has these goals:

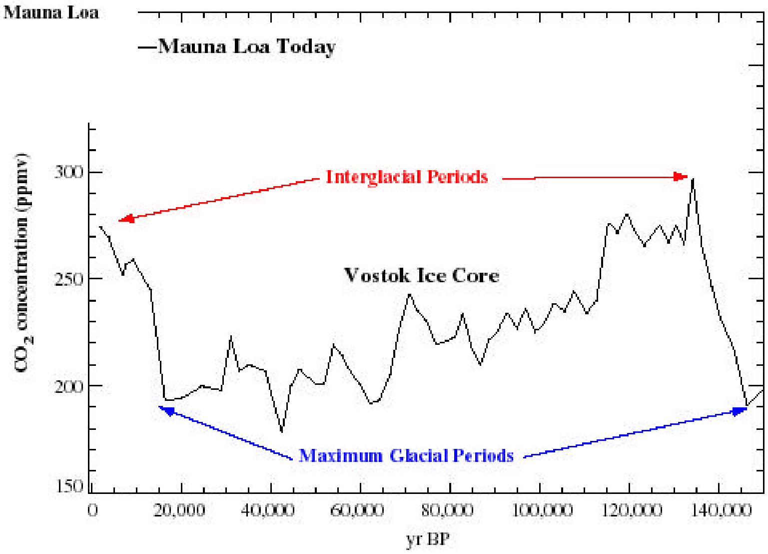
- provide a basic understanding of the Science of Earth Systems
    - The physical and biological processes governing the Earth's energy budget, hydrologic cycle, and major biogeochemical cycles (Carbon and Methane)
    - How these systems and cycles have changed through Earth's history
- provide and introduction to the technologies driving current research in Earth System Science
    - Remote Sensing
    - Computer Modeling
    - The Internet

Here is an example of the importance of Earth System Science. Below is what has arguably been called the most important figure produced in the geosciences during the past half-century. It is the time-series of the concentration of carbon dioxide in the atmosphere at Mauna Loa, Hawaii, developed by Charles Keeling and colleagues. There is no doubt



Keeling, C.D, and Whorf, T.D., Atmospheric CO_2 Concentrations - Mauna Loa Observatory, Hawaii, 1958-1996.

that this curve shows the increase in atmospheric carbon dioxide that has resulted from fossil fuel emissions and land cover changes. In fact the question is not whether the observed increase in carbon dioxide is the result of human activity, but rather how come it has not increased more since it is known humans releasing more carbon dioxide than is showing up in the atmosphere. Later in the class we will examine the potential 'missing sink' where this carbon dioxide appears to be being sequestered.



Meanwhile, back to the point... What exactly does this increase mean? An environmentally-inclined person might say this means it is necessary that we stop driving sport-utility vehicles and all drive the new VW bug otherwise we will bring the apocalypse upon ourselves. A more economically oriented person might say, he we have only increased carbon dioxide 80 parts per million, there is absolutely no reason to do anything.

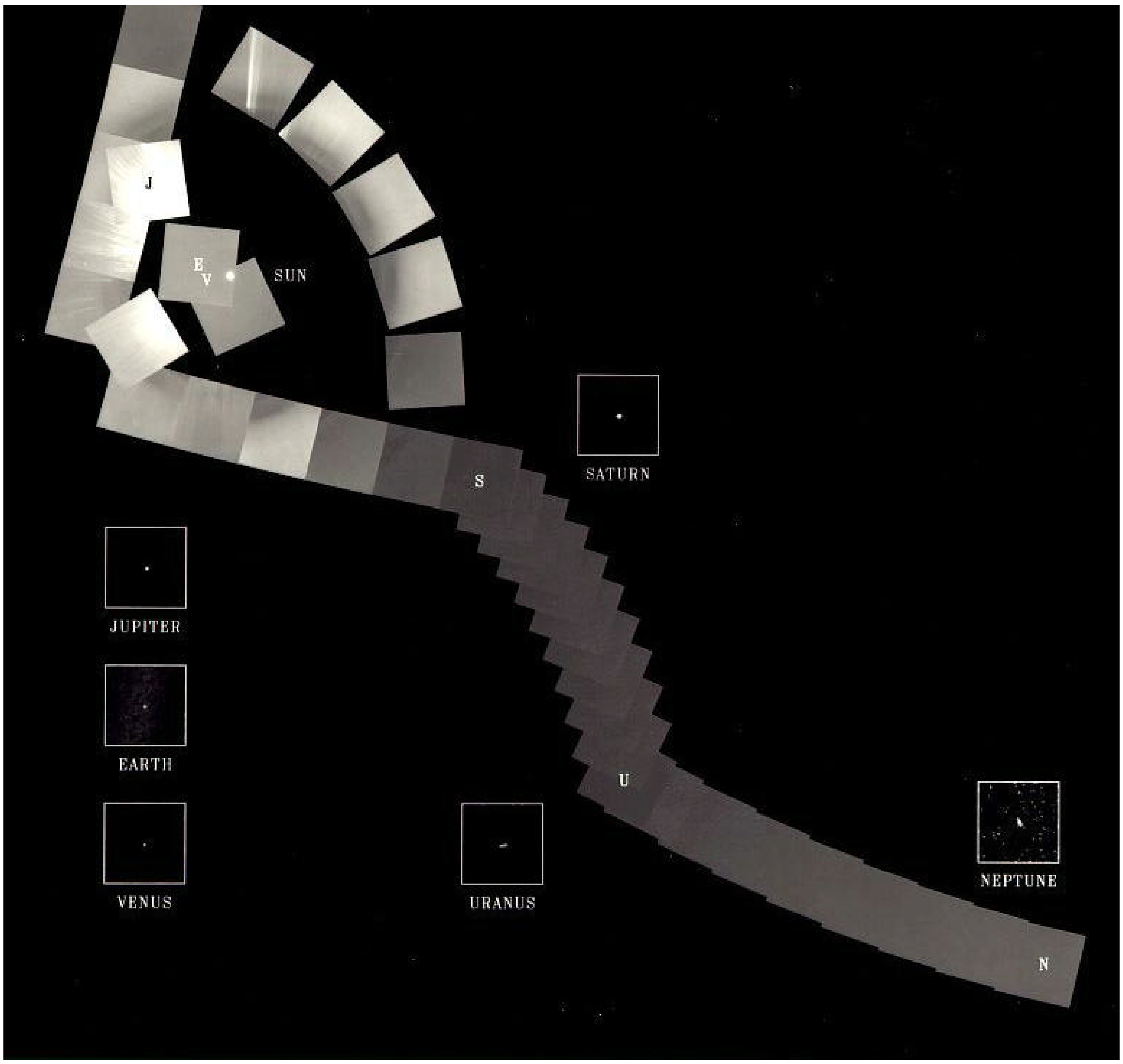
How do we select which, if any, of these admittedly stereotyped attitudes is correct?

The answer lies in understanding both the processes controlling the amount of carbon dioxide in the atmosphere and knowing the history of carbon dioxide in the atmosphere through time. For instance, maybe the second most important figure produced by the geosciences over the last half-century is the concentration of atmospheric carbon dioxide over the past 150,000 years as determined from air bubbles trapped in an ice core taken from Antarctica. This curve clearly shows that the increase in carbon dioxide since pre-industrial times is approximately that seen between glacial and interglacial times.

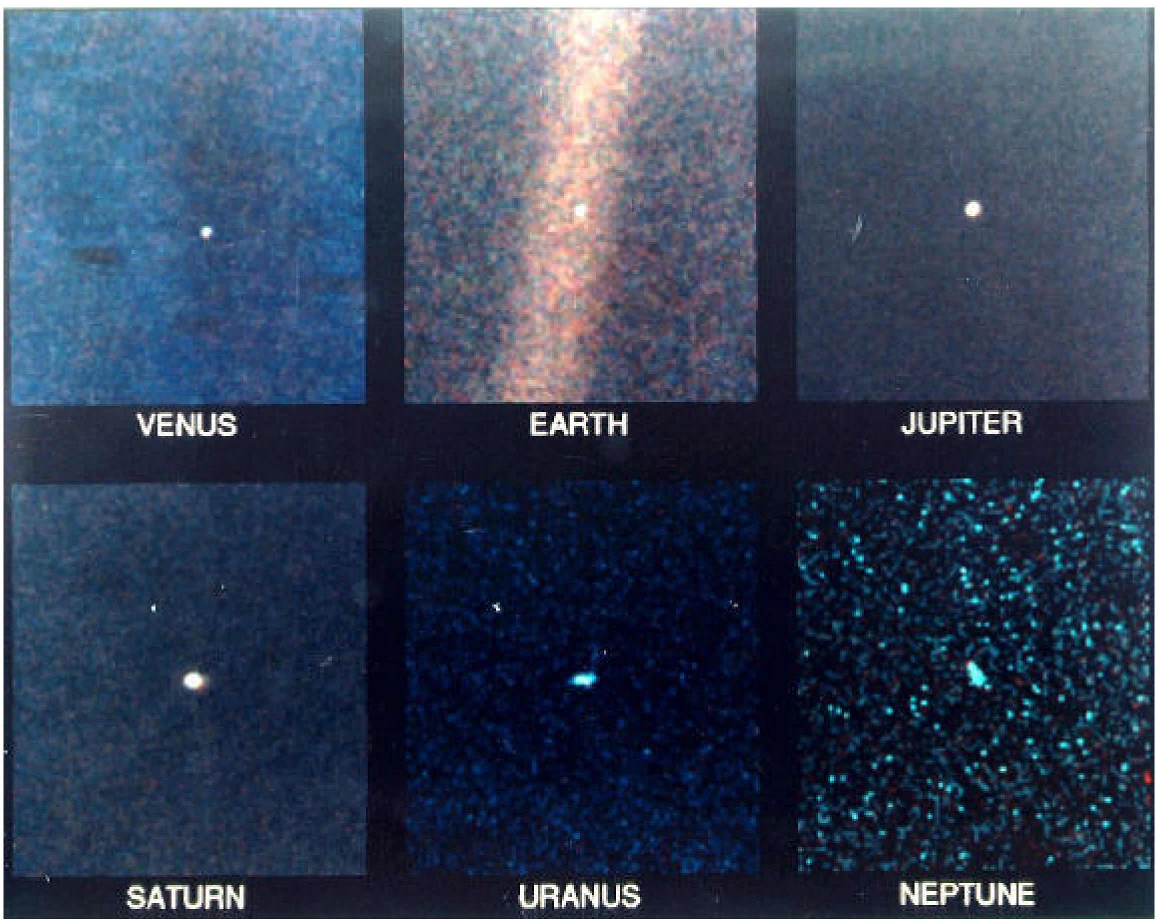
Such dramatic changes in carbon dioxide where of course accompanied by large climatic changes. While this comparison does not provide a policy solution to the problem of carbon dioxide emissions, it does point out the need for understanding the earth system in order to understand complex questions about global climate change.

Footnote

Carl Sagan further attempted to help us redefine our position in the universe by persuading NASA to take pictures of our Solar System using the Voyager Spacecraft as they passed beyond the orbit of Pluto. These revealing pictures are shown below.



JPL PRESS RELEASE The cameras of Voyager 1 on Feb. 14, 1990, pointed back toward the sun and took a series of pictures of the sun and the planets, making the first ever "portrait" of our solar system as seen from the outside. In the course of taking this mosaic consisting of a total of 60 frames, Voyager 1 made several images of the inner solar system from a distance of approximately 4 billion miles and about 32 degrees above the ecliptic plane. Thirty-nine wide angle frames link together six of the planets of our solar system in this mosaic. Outermost Neptune is 30 times further from the sun than Earth. Our sun is seen as the bright object in the center of the circle of frames. The wide-angle image of the sun was taken with the camera's darkest filter (a methane absorption band) and the shortest possible exposure (5 thousandths of a second) to avoid saturating the camera's vidicon tube with scattered sunlight. The sun is not large as seen from Voyager, only about one-fortieth of the diameter as seen from Earth, but is still almost 8 million times brighter than the brightest star in Earth's sky, Sirius. The result of this great brightness is an image with multiple reflections from the optics in the camera. Wide-angle images surrounding the sun also show many artifacts attributable to scattered light in the optics. These were taken through the clear filter with one second exposures. The insets show the planets magnified many times. Narrow-angle images of Earth, Venus, Jupiter, Saturn, Uranus and Neptune were acquired as the spacecraft built the wide-angle mosaic. Jupiter is larger than a narrow-angle pixel and is clearly resolved, as is Saturn with its rings. Uranus and Neptune appear larger than they really are because of image smear due to spacecraft motion during the long (15 second) exposures. From Voyager's great distance Earth and Venus are mere points of light, less than the size of a picture element even in the narrow-angle camera. Earth was a crescent only 0.12 pixel in size. Coincidentally, Earth lies right in the center of one of the scattered light rays resulting from taking the image so close to the sun. (NASA Photo Numbers P-36087A, 90-H-401)



JPL PRESS RELEASE These six narrow-angle color images were made from the first ever "portrait" of the solar system taken by Voyager 1, which was more than 4 billion miles from Earth and about 32 degrees above the ecliptic. The spacecraft acquired a total of 60 frames for a mosaic of the solar system which shows six of the planets. Mercury is too close to the sun to be seen. Mars was not detectable by the Voyager cameras due to scattered sunlight in the optics, and Pluto was not included in the mosaic because of its small size and distance from the sun. These blown-up images, left to right and top to bottom are Venus, Earth, Jupiter, and Saturn, Uranus, Neptune. The background features in the images are artifacts resulting from the magnification. The images were taken through three color filters -- violet, blue and green -- and recombined to produce the color images. Jupiter and Saturn were resolved by the camera but Uranus and Neptune appear larger than they really are because of image times. Earth appears to be in a band of light because it, coincidentally lies right in the center of the scattered light rays resulting from taking the image so close to the sun. Earth was a crescent only 0.12 pixel in size. Venus was 0.11 pixel in diameter. The planetary images were taken with the narrow-angle camera (1500 mm focal length). (NASA Photo Numbers P-36089C, 90-HC-380)

References

Required Reading

Johnson, D.R., Ruzek, M., and Kalb, M. 1997. What is Earth System Science? *IGARSS 97*. pp. 688-691. (attached).

World Wide Web Sites of Interest

- NASA's Mission To Planet Earth
  http://www.hq.nasa.gov/office/mtpe/index.html
- National Space Science Data Center Photo Gallery
  http://nssdc.gsfc.nasa.gov/photo_gallery/photogallery.html
- Universities Space Research Association (USRA) Earth System Science Education Program
  http://www.usra.edu/esse/ESSE.html

What is Earth System Science?

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Abstract - Given the concerns that humankind is impacting the earth's physical climate system, a broader concept of the earth as a system is emerging. Within this concept, knowledge from the traditional earth science disciplines of geology, meteorology and oceanography along with biology is being gleaned and integrated to form a physical basis for Earth System Science. The broader concept of Earth System Science has also come to include societal dimensions and the recognition that humanity plays an ever increasing role in global change.

The Earth System Science concept fosters synthesis and the development of a holistic model in which disciplinary process and action lead to synergistic interdisciplinary relevance. However, the development both conceptually and physically of the earth system model and its quantitative assessment in the classroom and laboratory is a continuing, formative processes which requires nurturing and commitment to eclectic learning beyond one's discipline. The intersection of disciplinary specialties often provides the most fertile and interesting fields for study, but is easily sidetracked by traditional disciplinary interests and limited understanding.

In its purest sense there should be no conflict between a discipline's interests with emphasis on specifics and depth and the demands for the interdisciplinary focus for Earth System Science and Global Change. Addressing the scientific issues of Earth System Science demands both breadth across disciplines and depth within disciplines to meet the future extremely difficult challenges of Agenda 21. In the emergence of Earth System Science as an effort to address Agenda 21 challenges, there is also an overriding need to embrace the interests of a broader range of disciplines than those which traditionally have represented earth science.

For the past six years the Cooperative University-based Earth System Science Education Program (ESSE) has been developing undergraduate Earth System Science courses, curricula and degree programs at forty-four colleges and universities throughout the country. The experience from these efforts has helped to create content and the means by which Earth System Science is being offered successfully at the college and university level. Earth System Science courses offer unusual opportunities to incorporate fundamental understanding with a broad appreciation of systems concepts and observational dimensions. In this paper trans-disciplinary concepts and applications to the Earth System are examined, and a strategy to build a repository of educational resources which bridge across disciplines is examined.

THE CHALLENGE OF AGENDA 21

Agenda 21 represents an international consensus on actions necessary to move the world towards the goal of truly sustainable development. It is an agenda for the 21st Century, as adopted by the United Nations Conference on Environment and Development (UNCED) at the "Earth Summit" meeting in June 1992 in Rio de Janeiro, Brazil. Agenda 21 takes a holistic approach to sustainable development and recognizes the interrelationships between people, the environment, and the economy [1].

There is a critical need for creating an orderly, comprehensive, interdisciplinary Earth System Science and Global Change curriculum in order to develop and evolve the underlying science and knowledge that forms the foundation for understanding and policy discussion by the government, economic, industrial, agricultural, regulatory and other societal interests as referenced in Agenda 21. The current state of insight into global sustainability within our society is minimal with respect to factual information and its interpretation. The aim must be to develop understanding of the interplay among the relevant societal endeavors of Global Change in relation to the Earth System and global sustainability.

As an abstract entity, the multi-dimensional nature of the knowledge space of the Earth System Science and Global Change setting remains to be determined. Clearly, the geosciences and other relevant disciplines have explored the subspace of their individual interests. However, the subspaces embodied within the larger setting that form the intersection among the disciplines are the fertile ones which need to be traversed and studied extensively. The only means of traversing these interesting intersecting subspaces is for disciplinary scientists to lock arms and through exchange of past, current and future information and creative insight develop all the dimensions of the knowledge space needed for Earth System Science and Global Change. The necessary talent that spans the range of disciplines and interests needed for this effort does not reside within any single government agency, university, small group of universities or regional activity. The development of an ordered and comprehensive Earth System Science and Global Change curriculum over the coming decade can only be accomplished through broadly based collaboration.

The objectives of this paper are twofold: One is to summarize certain underlying tensions that exist in developing the larger dimensions of Earth System Science within universities and between disciplines; the other is to describe an approach to creating a repository of education resources in Earth System Science which avoids disciplinary barriers by focusing on topics which bridge across disciplines and utilizes data bases and information from NASA's Mission to Planet Earth. The overall strategy of the ESSE Program, in effect, creates the Senate of the Interested in Earth System Science and Global Change education by engaging participants from the larger university setting who actively commit their time and energy in classroom instruction and shared curriculum development. A decade of effort or more will be needed before the integration of specific disciplinary interests into a comprehensive Earth System Science discipline relating to Global Change emerges. While many faculty are interested, the actual percentage of faculty who are committed to the pursuit of Earth System Science education is still relatively small.

EARTH SYSTEM SCIENCE EMERGES

A major effort of NASA's Office of Mission to Planet Earth (MTPE) is to provide for a global observational capability and to ensure that the data collected bear on the scientific and societal challenges that attend Earth System Science and Global Change. The acquisition of a global database for the Earth System is a massive undertaking in itself. The interpretation and utilization of global datasets are equally demanding. Data are meaningful and useful insofar as information is gained concerning structure and/or process within the Earth System. A key determining factor as to whether data provides information is an underlying framework or model - physical, biological, economic, statistical, etc. The model may be a simple understanding of cause and effect from experience or it may be based on the governing equations of physics where cause and effect stem from first principles. Apart from whether there is information in data, the framework or model to describe a system state and process which evolves is essential. Not only is it important for advancing scientific understanding and reducing uncertainty, but it is equally important for meaningfully informing society.

To realize the potential benefits from NASA's effort requires an informed society that understands and appreciates the interdependency of the Earth's physical climate system with all of life. Clearly classroom education within the nation's colleges and universities is an important dimension leading to an informed society concerning the Earth System. To achieve the larger need of developing a knowledge base for Earth System Science, an infrastructure within education is required that fosters collaboration and integrates relevant knowledge and resources currently residing within many different disciplines. The NASA/USRA Cooperative University-based Program in Earth System Science Education provides an infrastructure which brings together scientific talent and interests of various disciplines in the classroom, the laboratory and the workplace and ensures integration of knowledge in the classroom from both disciplinary and interdisciplinary research efforts [2, 3]. Key resources are emerging through collaborative efforts involving broadband communications, Internet, computer networking and electronic libraries with archives for large earth science and other data bases.

The point of departure of the ESSE Program for the development of educational resources in Earth Systems Science was the NASA document "Earth System Science: A Closer View" [4]. In this document the "Bretherton Diagram", as it has come to be known, provided a structure which emphasized the physical climate system and biogeochemical cycles. Within these two broad areas, the emphasis was on physical, dynamical and chemical interactions within the state of the system, as represented by the atmosphere, the hydrosphere and the lithosphere. The emergence of the human dimension of global environmental change expanded greatly the breadth needed in offering Earth System Science and Global Change Science within universities. Here, the following definition of Global Change has proven to be useful for two reasons.

> Global Change is concerned with the nature and consequences of anthropogenic perturbations in the interacting physical, chemical and biological and social systems that regulate the environment supporting human life and influence the quality of that life on planet Earth [5].

One, although this definition broadens the scope of interests, the thrust is bounded in the sense that the emphasis is on anthropogenic perturbations involving interacting physical, chemical, biological and social systems that regulate the environment. Two, there is a mandate that the knowledge required to address Earth System Science and Global Change is broader than that which is gained from any one discipline or for that matter group of disciplines such as that represented by the geosciences; meteorology, oceanography, geology, hydrology, glaciology etc. Still the knowledge residing in the geoscience disciplines is central to emergence of Earth System Science as a holistic discipline. At the moment, there is considerable tension within and among disciplines within the university system as to how to incorporate Earth System Science and Global Change in course offerings and degree programs, even within the geoscience disciplines.

To a certain degree the tension is useful, since it brings about change. Inherent university traditions and practices still for the most part fail to emphasize interdisciplinary efforts in education directed towards Earth System Science and Global Change. This problem stems from the emphasis given to competitive strengths of disciplines, as opposed to the emphasis needed for collaborative interests across disciplines.

There is a danger, however, of the Earth System Science concept becoming diluted by generalities without gaining meaningful insight into the fundamental physical processes which govern the system. Historical, descriptive observations are critical aspects in understanding the physical basis for the Earth system, and have contributed enormously with such basic concepts as the heliocentric solar system and plate tectonics. However, physics, mathematics and chemistry are still the fundamental disciplines upon which quantitative analysis and process must be based. Fundamentals from these disciplines provide the necessary foundation for theory, modeling and applications in the geoscience disciplines and for understanding the physical, chemical and biological core of land, ocean, atmosphere and life processes which constitute the Earth System. A combination of fundamental and applied interdisciplinary knowledge provides fruitful avenues to explore the interface of the known and the unknown and thus understand the system as a whole.

A MODULE APPROACH TO EARTH SYSTEM SCIENCE AND LEARNING

Based on experiences among the ESSE participants over several years, it is apparent that the definitions of Earth System Science and Global Change are evolving and will continue to evolve, since the needs, perspectives and expectations of those who desire to integrate such topics and themes in their courses are extremely diverse. Thus, it is unrealistic to attempt to impose a single view of an organization and content for Earth System Science that would serve the needs of faculty whose perspectives could range anywhere from environmental economics to physical oceanography. Global change, especially, is not as much a fixed set of ideas that define a single curriculum, as it is a perspective.

In August, 1996, ESSE participants initiated a formal collaborative effort to create Earth System Science educational modules for utilization by ESSE participants, faculty, teaching assistants and students with the primary users of the ESSE modules being university and college faculty developing Earth System Science and Global Change courses. Fourteen teams of 3 - 5 ESSE faculty and teaching assistants are now creating flexible educational materials to be accessed electronically [6]. Module topics include:

Observing Systems and Remote Sensing
The Biosphere
Atmospheric Ozone
Economics, Sustainability and Nat Resources
The Antarctic
Earth Energy Budget
El Niño - Southern Oscillation
Hydrological Cycle
Earth System History
Biogeochemical Cycles
Human Population - Environment Interactions
Health and Climate Change
Soil Processes, Land Use, Land Cover Change
System Concepts and the Earth System

These materials are to be specifically designed for eventual electronic delivery through the ESSE sever [7]. In previous years, various strategies for organizing ESSE educational resource materials had been discussed, including the familiar disciplinary components of the geosphere, atmosphere, hydrosphere, biosphere and anthroposphere. However, the development around interdisciplinary topics was considered by ESSE participants to be the means of ensuring an interdisciplinary perspective. Other ways for conceptually organizing topics and content among and within modules may become apparent with time and experience. However, an advantage of computer-based and linked materials is that alternative conceptual frameworks are easily accommodated through customized indexing even after materials are created.

At the moment, modules are best viewed as organized collections of ìusefulî instructional resources organized around fourteen interdisciplinary topics. The number of module topics is expandable, as is the content within each. Structurally, each module is divided into a number of key issues or sub-topics as a second level of organization (Fig. 1). A module sub-topic is populated with resources or instructional materials designed to impart specific concepts or skills. A resource can be anything that has proven to be useful based on experience in undergraduate instruction, and can be applied directly in the classroom by others. Resources are written background materials, bibliographies, annotated images, lab or model exercises, demonstrations, activities broadly defined and documented, etc. A resource could be something newly developed in response to need, or could be existing materials from among ESSE or collaborating schools. A resource could be the modification, adaptation, compilation or presentation in a unique and particularly useful way of currently available materials, concepts or data, but would not duplicate materials already easily available from non-ESSE sources. ESSE modules would acknowledge and point to existing materials on the internet or elsewhere.

While each ESSE team has flexibility in their development of focus, approach and content, each module is expected to share certain attributes. Each module will contain resource materials that are developed, presentable and adaptable to undergraduate students at various levels of intellectual readiness, survey to senior. Module content will be scientifically accurate. Either the module or subtopics will be readily applicable in the classroom or lab and will include substantive components of the human and social dimensions of global change wherever possible. Materials will be suitably formatted for electronic delivery, and be innovative in their use of internet-based resources and computer-based tools, applications, and models. No specific size limits are placed on any resource except those dictated by reason and time constraints. The overarching criteria for a resource to be included in an ESSE module (directly or indirectly through web links) are content applicability and educational utility. Being central to NASAís mission in Earth System Science, *Remote Sensing*, *Systems Concepts, and Understanding Models* will be common threads that run through all modules. All ESSE resources will be considered in the public domain.

Efforts are being made to ensure professional input on pedagogical considerations and assessments for the program. Education specialists within ESSE, as well as outside collaborators, are available to advise the program and teams in these areas. With many approaches facilitating effective learning, there is a need for flexibility. No single pedagogical approach is being promoted or considered. However, each team is to consider effective and cohesive pedagogical approaches. An ESSE shell or template surrounding all modules and resources will offer a common user interface that provides entry documentation explaining the context, purpose and use of the material, and will include lists of key concepts and questions in the spirit of inquiry-based learning.

SUMMARY

In recognition of the diversity of interests and expertise concerning Earth System Science that reside within universities and research organizations and the need to develop breadth and depth that reside within disciplines, a strategy adopted within the ESSE program for the development of classroom educational resources is to create electronic modules based upon topics that are of central importance to Earth System Science. The emphasis on topics of importance avoids the compartmentalization of teaching Earth System Science by "subdisciplines", since in all cases the topics focus on critical issues that bridge across the geosciences and other relevant disciplines. There is emphasis on evolving course content as the underlying knowledge base develops through acquisition, analysis and interpretation of global data. This ensures the development of holistic perspectives of Earth System and Global Change Science and introduces students to the underlying important issues and challenges of Agenda 21.

ACKNOWLEDGMENTS

The authors acknowledge the contributions of time and expertise of the participants at the ESSE Module Development Workshop in Coolfont, WV August 12 - 16, 1996. The NASA/USRA Cooperative University-based Earth System Science Education Program is supported by a grant from NASA's Mission to Planet Earth (NAGW-4831)

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[2] D. R. Johnson, M. Ruzek, M. Kalb, "Earth System Science Education - An Internet-based Electronic Curriculum" in *Proceedings of the 1995 International Geoscience and Remote Sensing Symposium (IGARSS '95*), Florence, Italy pp. 572-574

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[6] M. Kalb, D. Johnson, M. Ruzek "Evolution of the Cooperative University-based Program in Earth System Science Education", Proceedings of the American Meteorological Society Sixth Symposium on Education Long Beach, CA, February, 1997 pp. J1-4

[7] The Earth System Science Education WWW Home Page http://www.usra.edu/esse

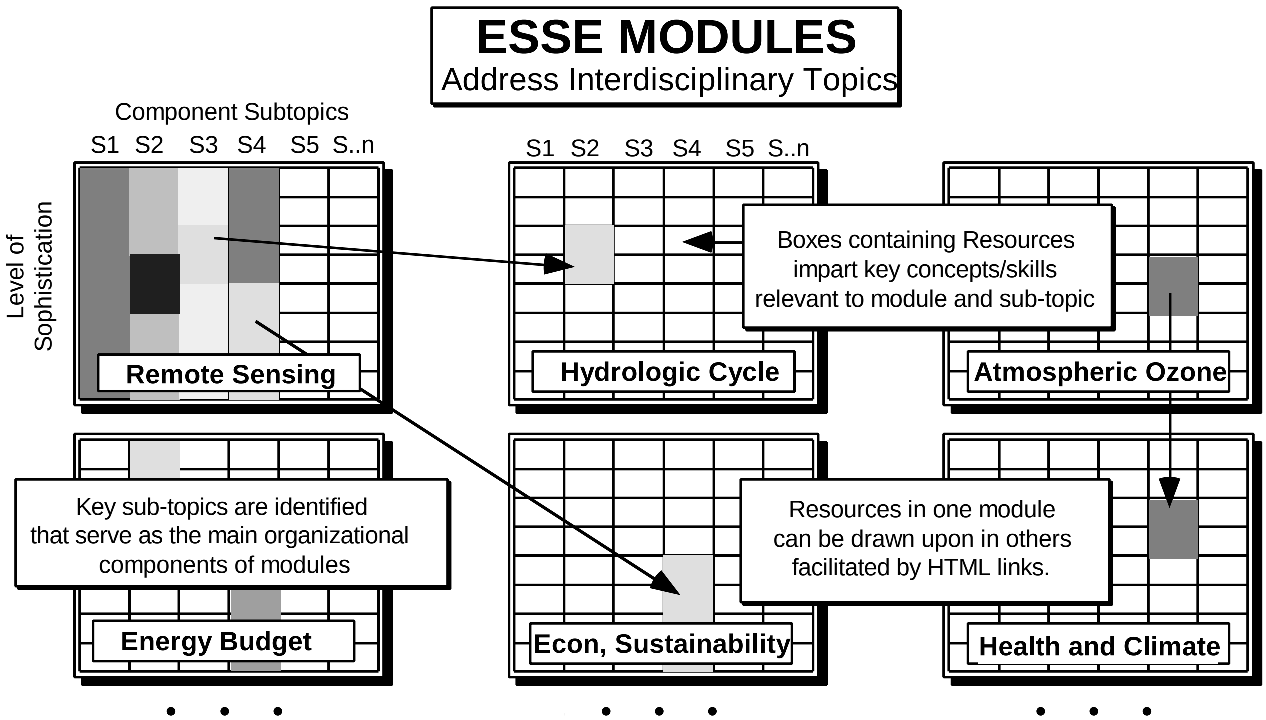
ESSE MODULES
Address Interdisciplinary Topics
Component Subtopics
S1 S2 S3 S4 S5 S..n
Level of Sophistication
Remote Sensing
S1 S2 S3 S4 S5 S..n
Hydrologic Cycle
Boxes containing Resources impart key concepts/skills relevant to module and sub-topic
Atmospheric Ozone
Key sub-topics are identified that serve as the main organizational components of modules
Energy Budget
Econ, Sustainability
Resources in one module can be drawn upon in others facilitated by HTML links.
Health and Climate

Figure 1